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ENERGY CONVERSION OF A PENDULUM WAVE ENERGY CONVERTER MOUNTED TO THE SEABED

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ABSTRACT

Hydraulic systems have been applied as a power take-off device in wave energy converter since the systems have high robustness and controllability under severe load conditions. To maximize power generation, optimization of the combination of pendulum dimensions, hydraulic parts and generator is required under various sea states. Moreover, from the viewpoint of grid connection, maximization of output power and smoothing have to be satisfied simultaneously. In this research, the power conversion simulation which considered from the wave to the generator rotation was created to optimize the pendulum wave energy converter,

KEYWORDS

Hydraulic system, Pendulum, Simulink, Wave energy converter

1. INTRODUCTION

The pendulum type wave power generator (WEC) swings a submerged pendulum by the power of the wave, and drives the generator by the swing. Muroran Institute of Technology 1), the University of Tokyo 2) has developed a pendulum type WEC with a rotating shaft in the air. While, AW-Energy's WaveRoller3) and Oyster4) developed a pendulum type WEC with a rotating shaft on the seabed.

These devices employed a hydraulic drive as a power take-off(PTO) device. Since the hydraulic system has high robustness and controllability under severe load conditions, it has been adopted as a PTO device for WECs 5) -7).

However, since sea states changes depending on the sites, it is necessary to optimize the combination of pendulum dimensions, hydraulic components, and generators to maximize power generation. From the viewpoint of grid interconnection, the output power must be maximized and smoothed simultaneously. Therefore, in this research, a power conversion simulation from wave to generator was created to optimize the entire pendulum-type wave energy converter,

2. POWER CONVERSION

It was assumed that a pendulum with a width of 5 m, a height of 4.5 m, and a depth of 0.5 m was installed on the seabed at a depth of 5 m. Fig. 1 shows the concept of a fixed-type pendulum WEC. It is assumed that the pendulum is installed on a horizontal seabed at a depth of 5 m and the rotation axis is 0.5 m above the seabed.

The power of the incident wave is absorbed by a PTO at the center of rotation of the pendulum. The rotation speed of the pendulum is increased by the gearbox and transmitted to the hydraulic circuit. The pendulum consists of a 1cm thick steel plate. The mass is 4251 kg and the moment of inertia around the rotating shaft is 32439 kg m2.

The concept of the hydraulic circuit is shown in Fig. 2. The sending of hydraulic oil from the actuator is reversed by the incoming wave and the outgoing wave, which reverses the rotation of the generator and disturbs the power. To prevent reverse rotation of the generator, two-directional flow sent from the actuator is rectified by a bridge circuit combined with check valves. And accumulators are used to prevent pulsation caused by waves.

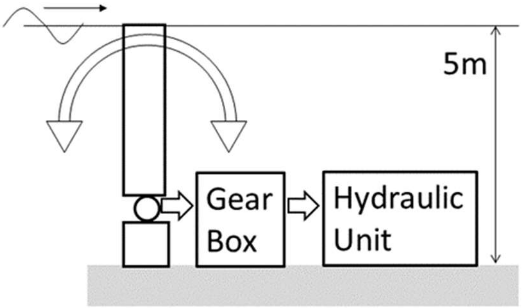

Figure 1 Concept of bottom fixed pendulum wave energy converter

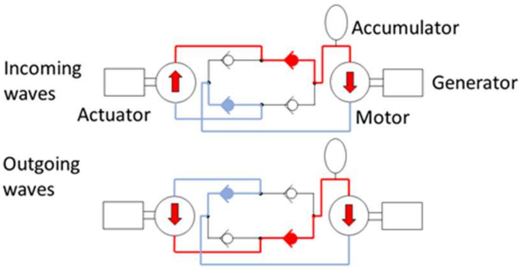

Figure 2 Hydraulic energy conversion system

2.1 Pendulum power conversion

The equation of motion of the pendulum is expressed by equation (1).

$$I\ddot{\theta} = F_{exc} + F_{rad} + F_{PTO} \tag{1}$$

I is the moment of inertia around the rotation axis, F_{exc} is wave exciting force, F_{rad} is the radial force, and F_{PTO} is the reaction force of the PTO. F_{rad} is expressed by equation (2) using a convolution integral.

$$F_{rad}(t) = -A_{\infty}\ddot{\theta} - \int_0^t K_{\tau}(t-\tau)\dot{\theta}(\tau)d\tau \tag{2}$$

A_{∞} is the added moment of inertia at infinite frequency, K_{τ} is the memory function, and is expressed by equation (3) with wave damping B (ω).

$$K_{\tau}(t) = \frac{2}{\pi}\int_0^{\infty} B(\omega)\cos(\omega t)d\omega \tag{3}$$

The wave exciting force is given by equation (4) for a regular wave.

$$F_{exc}(t) = \Re\left[R_f \frac{H}{2} F_{exc}(\omega)e^{i\omega t}\right] \tag{4}$$

R_f is the ramp function, H is the wave height of the incident wave, and F_{exc} is the wave exciting vector. $\Re$ takes the real part of a complex number. For irregular waves, the water surface displacement is represented by a superposition of regular waves. Each component is obtained from the wave spectrum S(w). The wave exciting force is defined by equation (5).

$$F_{exc}(t) = \Re\left[R_f \int_0^{\infty} F_{exc}(\omega_t)e^{i(\omega_{\tau}t+\phi)}\sqrt{2S(\omega_{\tau})}\,d\omega_{\tau}\right] \tag{5}$$

FPTO is expressed by equation (7).

$$F_{PTO}(t) = -C\dot{\theta} - K\theta \tag{6}$$

C is the damping coefficient of PTO, *K* is the spring constant. They are determined to maximize the absorption power in the site.

In this study, regular wave was assumed. The power conversion efficiency of the incident wave is the ratio of the absorbed power W_2 to the incident wave power W_1.

$$\eta = \frac{W_2}{W_1} \tag{7}$$

For regular waves, W_1 is expressed as (8)

$$W_1 = \frac{\rho g H^2 BC}{16}\left(1+\frac{2kh}{\sinh 2kh}\right) \tag{8}$$

Absorbed power was defined as the time average of the product of torque and rotational speed.

$$W_2 = \frac{1}{T}\int_0^T T_{rq}\dot{\theta}dt \tag{9}$$

The conversion efficiency of the pendulum in a regular wave with a wave height of H = 0.5 m and a period of T = 10 seconds. (8) was calculated for a combination of C and K. K = 1e6 [Nm/rad] and C = 1e6 [Nms/rad], which have high conversion efficiency, were selected. Figure 3 shows the conversion efficiency for incident waves with a wave height of 0.5 to 4.0 m and a period of 4 to 16 seconds at K = 1e6 [Nm/rad] and C = 1e6 [Nms/rad]. The figure shows high efficiency on the shorter wavelength. Figure 4 shows the absorbed power of the pendulum.

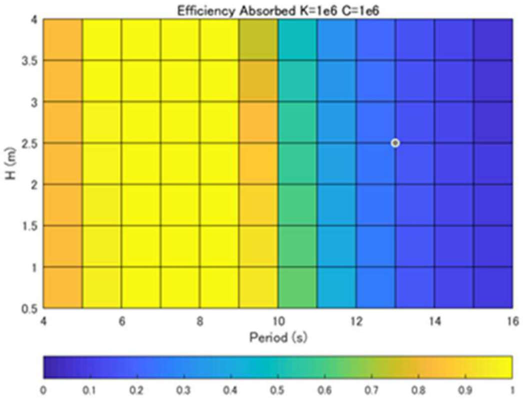

Figure 3 Absorbed efficiency

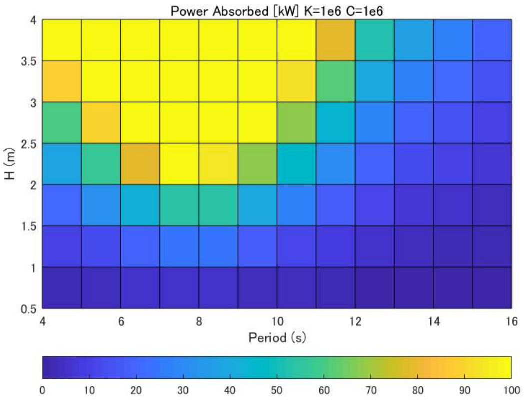

Figure 4 Absorbed power

2.2 Modeling hydraulic circuit

In the possible site, the wave height is less than 1 m, which corresponds to the area smaller than 10 kW in Fig. 4. Therefore, a hydraulic power conversion system using a 3.3kW generator was studied. Figure 5 shows the concept of the system, and Table 1 shows the specification of elements. Fig. 6 shows a picture of the experimental circuit, and Fig. 7 shows a draft of the circuit.

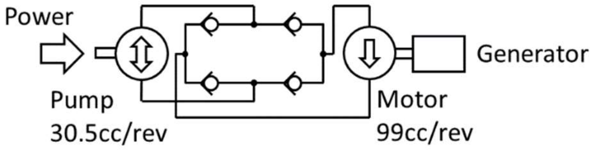

Figure 6 Concept of hydraulic circuit

Table 1 Specification of hydraulic elements

Parts	Type (manufacturer)	Specification
Hydraulic pump	MRF-03H (Mitsubishi Heavy Industries)	30.9cc/rev, 14MPa
Hydraulic motor	ME100 (Eaton)	99cc/rev
Generator	SKY-MG450 (Sky denshi)	3.3kW/300rpm, 15 Ohm, 48pole
Accumulator	NH-A21MP-LL5-AAC (Nippon Accumulator)	5.0L, 3.5MPa N2

Servo motor	HG-JR15K1M (Mitsubishi electric)	7.3kW/1000rpm

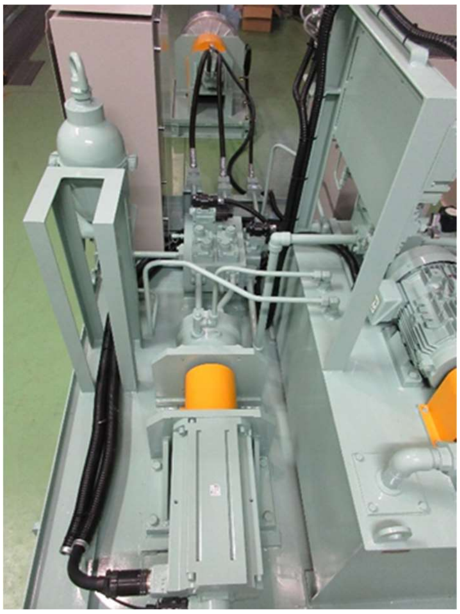

Figure 6 Picture of experiment facility

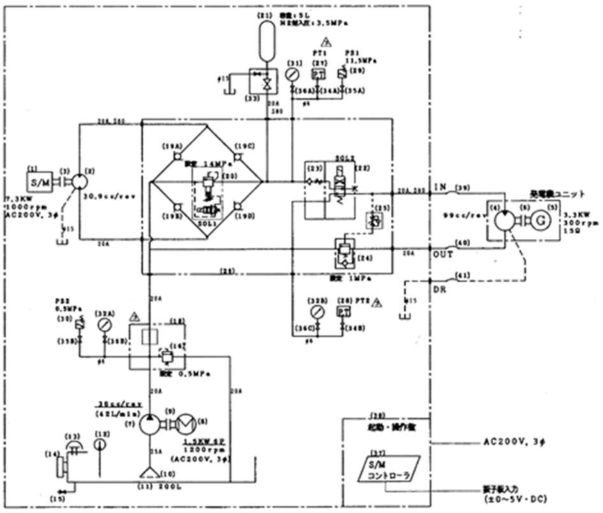

Figure 7 draft of hydraulic circuit

A Simulink model of the hydraulic circuit was created to select the elements to improve the conversion efficiency (Fig. 8). To verify the model, the differential pressure between the inlet and outlet of the hydraulic motor was compared. Figure 9 shows the differential pressure between the simulation and the experiment for a sinusoidal rotation speed with an amplitude of 1000 rpm and a period of 6 seconds. Although the differential pressure in the simulation was 1 MPa higher than the experimental results, the general tendency agreed.

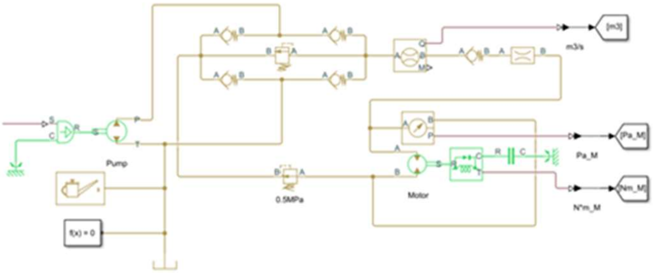

Figure 8 Simulink model of hydraulic power converter

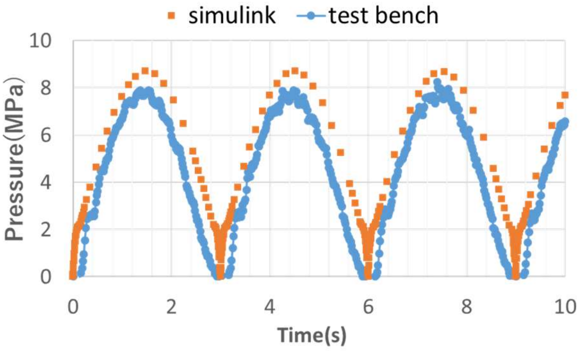

Figure 9 Comparison of pressure of working fluid in hydraulic circuit

2.3 Coupled calculation of pendulum and hydraulic circuit

Fig. 10 shows a power conversion simulation that coupled the pendulum described in section 2.1 and the hydraulic circuit described in section 2.2. Fig. 11 shows that the output of the hydraulic motor changes in phase with the pendulum. Negative absorbed power is converted into positive motor power by the bridge circuit. Since instability of motor power fluctuate the generator power, an accumulator that stabilize the output is required.

Figure 12 shows the motor output with an accumulator under the same wave conditions. The accumulator is set at an inlet of the motor. The accumulator is a gas-filled type with a total volume of 8e-3 m^3, a minimum gas volume of 4e-5 m^3, and an initial pressure of 7 MPa. Tt the start of operation, the accumulator discharge oil because the initial pressure of the accumulator is higher than the pressure in the hydraulic circuit. The pressure approaches a constant after approximately 20 seconds. Table 2 shows the mean and standard deviation of the output. When the accumulator is installed, the average output decreases by 0.87kW, while the standard deviation decreases by 1.67kW. The installation of an accumulator is inevitable for grid connection. The optimal specification of an accumulator is for further study.

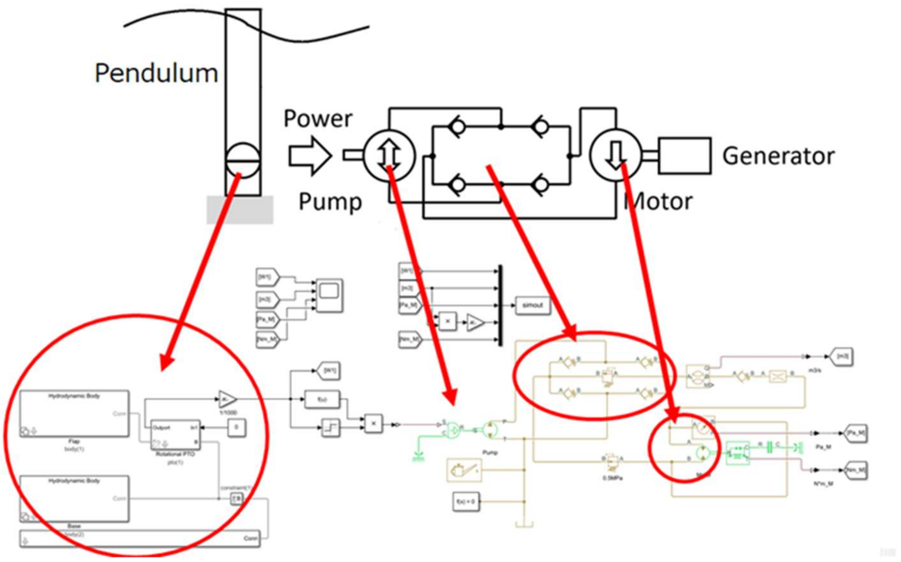

Figure 10 coupled model for pendulum and hydraulic circuit

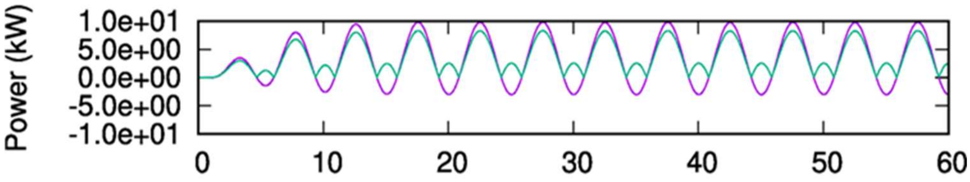

Figure 11 absorbed power of pendulum (purple) and output power of hydraulic motor without accumulator (green)

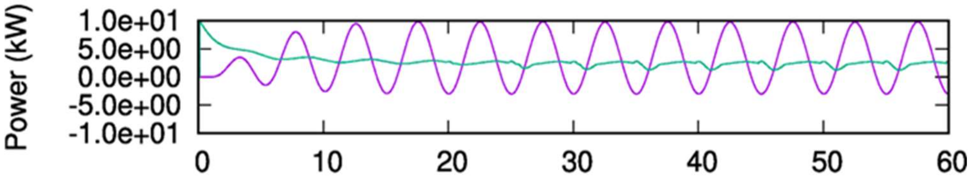

Figure 12 absorbed power of pendulum (purple) and output power of hydraulic motor with accumulator (green)

Table 2 Output power of hydraulic motor

Output power	Without Accumulator	With Accumulator
Averaged (kW)	3.64	2.77
Standard deviation (kW)	2.77	1.10

CONCLUSIONS

A power conversion simulation of a pendulum wave power generator installed on the seabed was created. In the simulation, the power conversion process of the pendulum and the hydraulic circuit was coupled. The effectiveness of the accumulator was demonstrated by simulating hydraulic power conversion under regular wave conditions. This simulation is useful for optimizing the equipment in the expected site. Future tasks are simulation of irregular waves and optimization of accumulator specifications.

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